3D-Reconstruction via Genetic Algorithms: Application to Metallic Fuel

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Introduction

The Problem of 3D Reconstruction

The knowledge of the 3D structure of **metallic fuel** is fundamental to determine material properties (such as **percolation threshold**).

Direct techniques available, e.g. FIB sectioning and reconstruction and MicroCT.

- Pros: direct 3D information;
- Cons: limited volumes can be reconstructed (either time consuming or **limited penetration range in dense material**) and FIB is destructive.

An alternative way is **inferring 3D information from 2D sections.**

- Pros: experimentally less challenging (particularly when applied to **highly radioactive fuels**) and is applicable to large volumes of material;
- Cons: 3D structures are inferred through an **inverse problem**, our scope being the reconstruction of media of which random 2D sections best resemble the experimental 2D sections

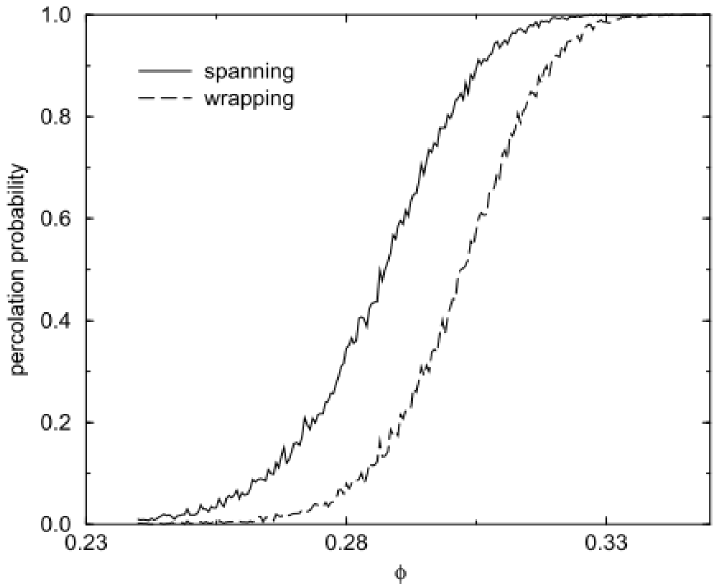
The purpose of this work is to introduce a methodology that allows to reconstruct **3D structure from 2D images and infer the property of Percolation.**

Introduction

Percolation Threshold

Percolation is a 3D property of the porous medium. It means that has established **interconnected porosity** so that there is a free path through the pores from one side to the opposite.

Percolation threshold is the **limit porosity (ϕ)** at which we have a **certain probability** that the **medium percolates.**



The knowledge of such property is of utmost importance for **fission gas release, and** in establishing good **irradiation performance** and **high burnups** in **metallic fuels**.

Overview of Metallic Fuels

Materials, Performance, and Design

Metallic fuels are usually composed of a binary (U-Zr) or ternary (U-Pu-Zr) alloy.

- Pros: applicability to **transmutation of minor actinides**, compatibility to **pyrometallurgic reprocessing** and **high thermal conductivity**.
- Cons: high **fission-gas-driven swelling** (meaning limitations in reaching high burnup).

Constraining swelling has proven **inefficient** (high **fuel-cladding mechanical interaction (FCMI)** resulting in **cladding failure** occurred).

Modern designs allow for **accommodating swelling** up to **30% volume**, at which point fuel has developed **interconnected porosity** and **fission-gas-release** occurs, **limiting FCMI**.

Percolation is therefore **extremely important** in establishing steady state irradiation performance and reach high burnups.

However, the **microstructure** of metallic fuel is **extremely complex**, due to the formation of **different material phases**, and poises serious challenges to any reconstruction procedure.

Overview of Metallic Fuels

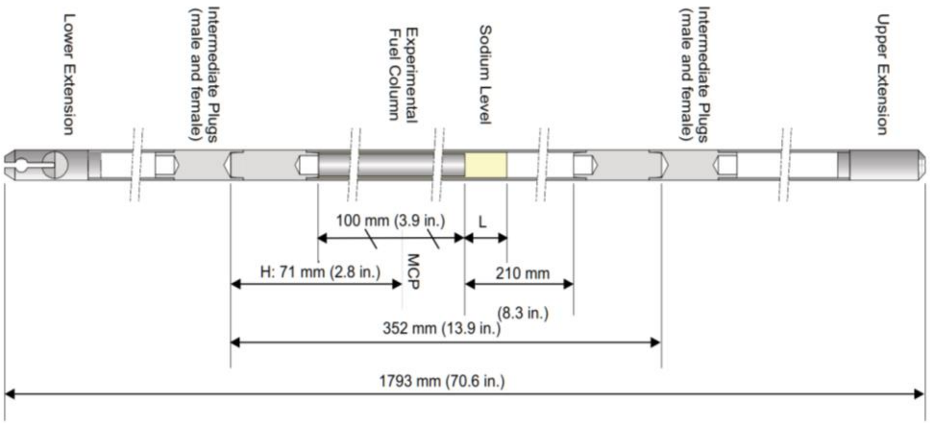
The FUTURIX-FTA irradiation campaign, DOE-1 metallic fuel

The **FUTURIX-FTA irradiation campaign** was a **U.S. DOE** and **French CEA** collaboration, to study **metallic** and **nitride fuels** for **actinides transmutation**.

DOE-1 metallic fuel was a U-29Pu-4Am-2Np-30Zr (ternary) alloy fuel. It was irradiated at 9.08% FIMA (fission of initial metal atoms).

Precipitation of insoluble fission gas generated a mostly **bubble-like coalesced porosity**.

Bubbles **nucleates**, **grow**, and then **coalesce**, generating pores of non-spherical shape.



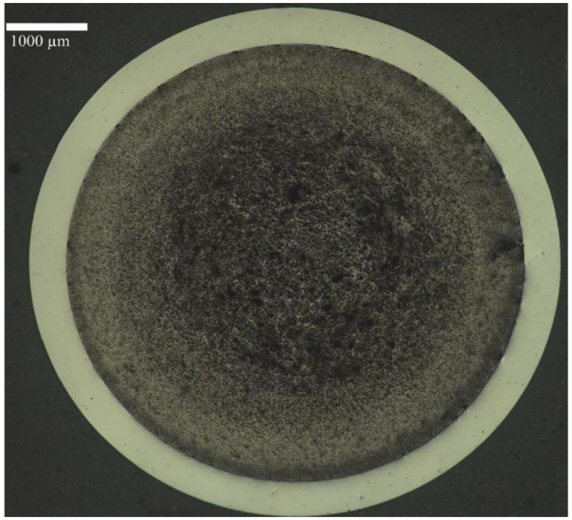
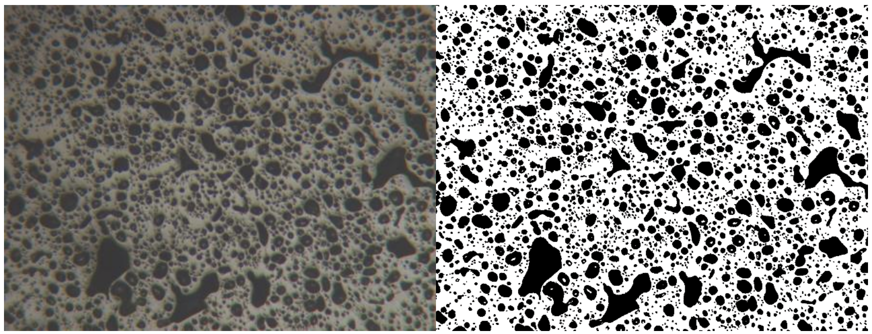


Image Analysis

Physical Information from Images



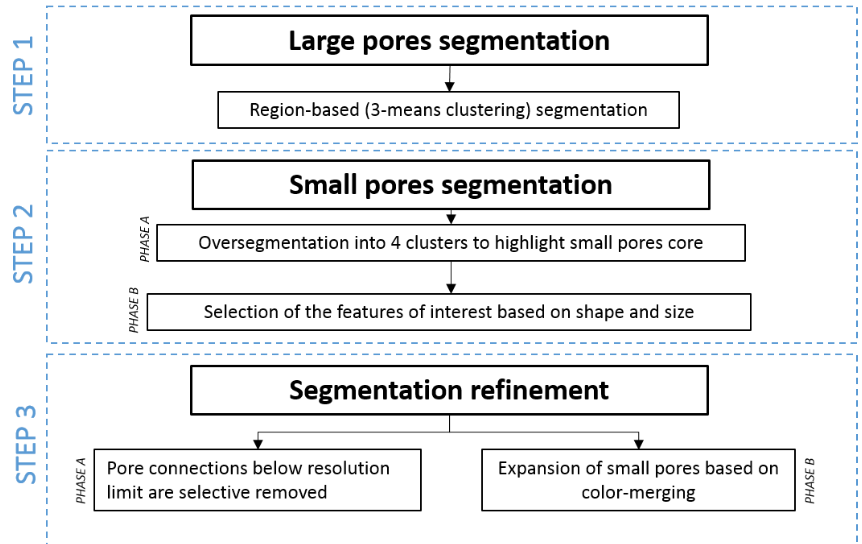
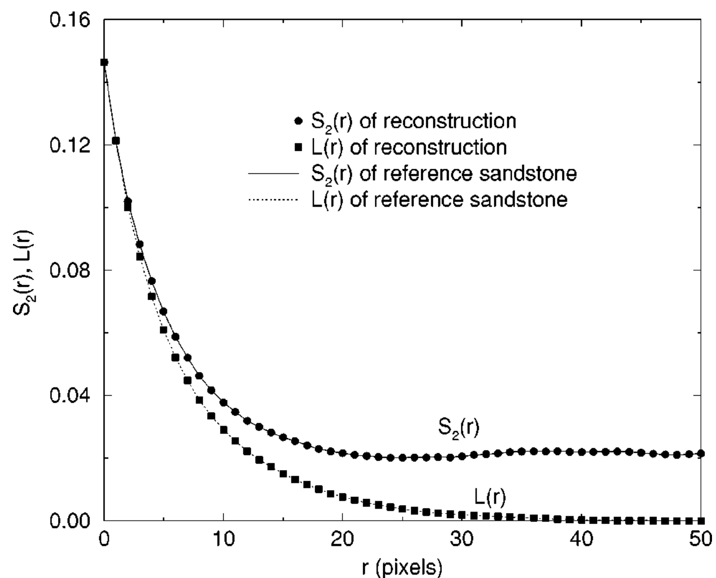


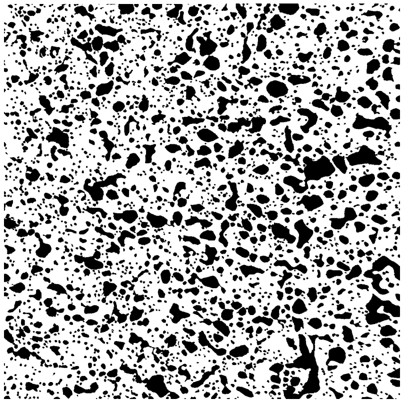
Image analysis is the primary method to obtain **quantitative information** from 2D microstructures.

The statistical information **fundamental to the reconstruction procedure** is extracted from processed binarized images (2D correlations and pore-size distribution).

Reconstruction Procedure

Random Heterogeneous Materials





A **Random Heterogeneous Material** (**RHM**) is the microstructural model adopted in this work.

- Composed by domains **two** or **more material phases**;
- **Isotropy** of the material.

RHM material phases are described in terms of **statistical correlations**:

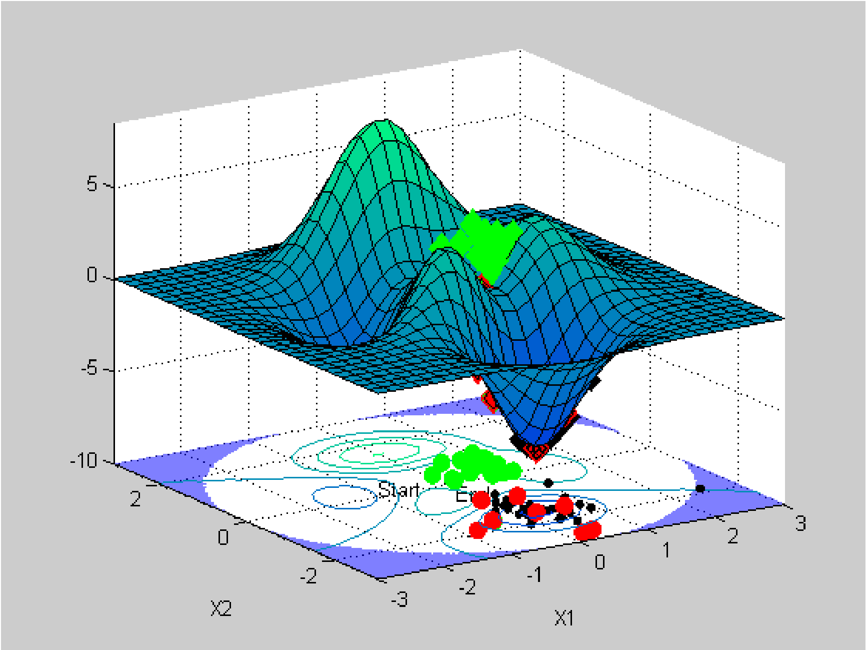
- **One-point correlation (porosity)**;
- **Two-point correlation (pore distribution)**;
- **Lineal-Path Function (pore connectedness)**.

They have important properties that describe the features of the RHM.

Reconstruction Procedure

Genetic Algorithms (1/2)

Heuristic methods treat the reconstruction as an **optimization** problem, and **evolutionary algorithms** deal with the optimization with an evolutionary approach.



Advantages:

- **Global Search** Method;
- Good **Exploration** and **Exploitation** properties;
- Produces a family of best solutions.

Disadvantages:

- Random procedure;
- **Heavy** computational weight.

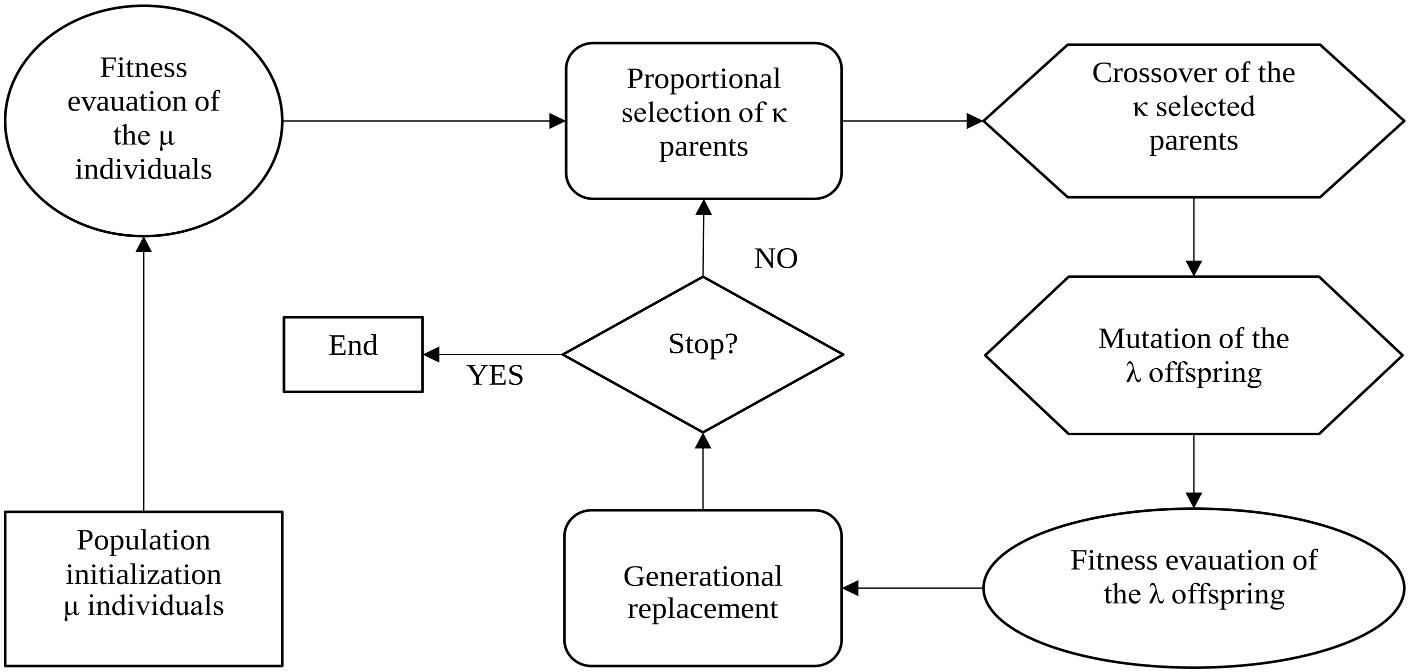
Reconstruction Procedure

Genetic Algorithms (2/2)

The GA is constituted by an initialization step and an iterative loop (**generation**).

- **Initialization** samples random individuals within the search space.
- **Generation** produces for each loop a new population of solutions.

The newly generated populations will be **better** than the previous populations.



Reconstruction Procedure

Fitness function

Optimization in a genetic algorithm is performed on the **fitness function**.

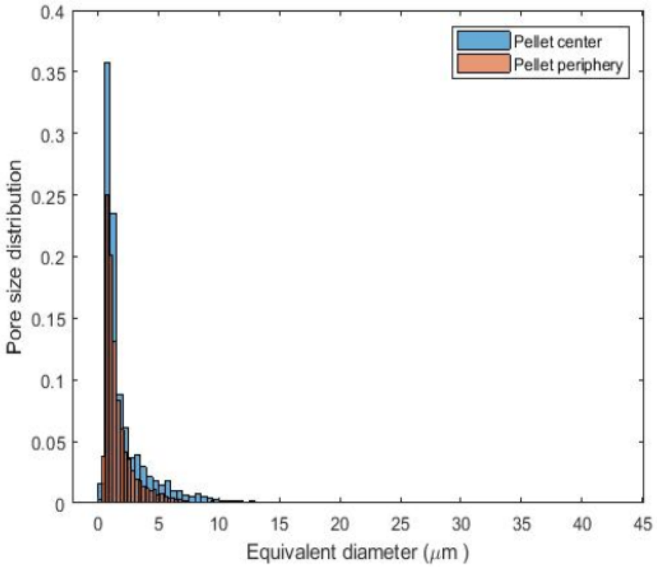
The fitness function defines the problem. It returns a **fitness** value, in this case the *"distance"* between each **section cut from reconstructed 3D media** and the **reference section**.

Minimizing the fitness values means minimizing the difference between the sections.

The fitness in this work is the difference between:

- **2D pore number**;
- **2D average equivalent radius**;
- **2D standard dev. of equivalent radius**.

We have convergence on **2D pore-size-distribution.**



Reconstruction Procedure

State-of-the-Art

Most of the reconstruction methods already proposed use as fitness function the least square difference between the correlations.

We avoid to proceed this way, since it is too constraining, and lacks generality. We instead use correlations for validation of the proposed procedure against known artificial data.

In the end, we want an algorithm to minimize the difference between the reference (measured) and reconstructed 2D sections that yields minimum difference between the 3D structures.

Inverse problem, uniqueness of the solution not guaranteed

2D images → **Morphological information (statistics, correlation functions…)** → **3D structure**

↓

Macroscopic properties

Reconstruction Procedure

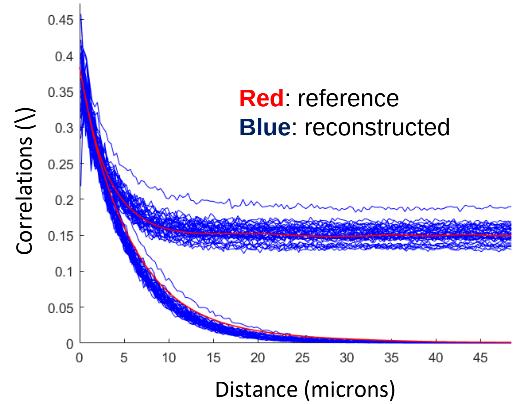
Validation against Known Artificial Data

The **GA** was validated with application to **artificial, known 3D microstructures**. It achieved **good convergence** on the **2D sections** cut from reconstructed **3D media**.

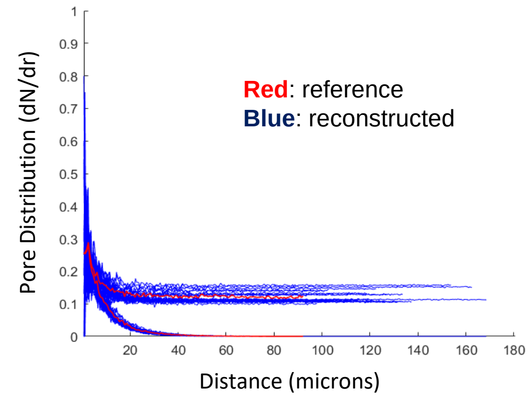
This yields good 3D correspondence, **as seen by direct comparison of 3D properties** of the reference and reconstructed media. We produced a family of **statistically equal** realizations.

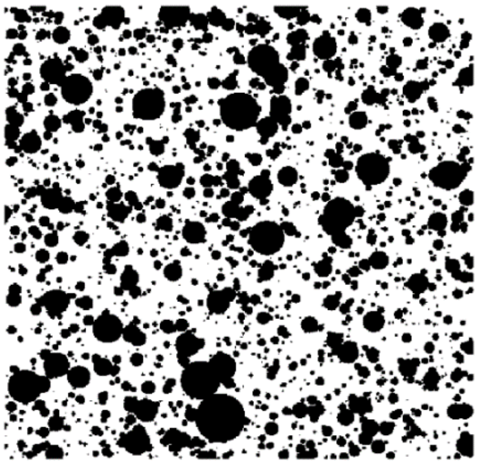
We have a confidence interval of 3D pore combinations generating the 2D sections. **This is fundamental in defining the confidence interval of 3D properties**.

Correlations 2D

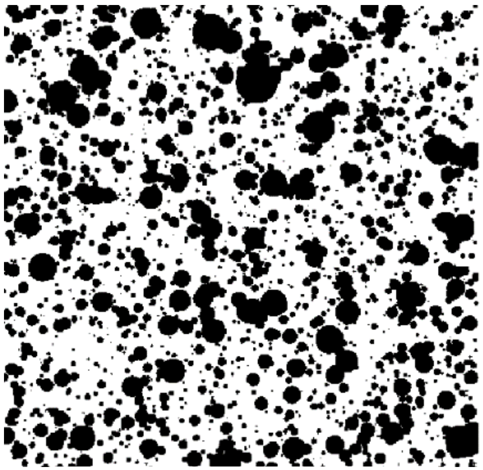


Correlations 3D





Reference 2D Section



Reconstructed 2D Section

Results

Reconstruction of the Experimental Data (1/3)

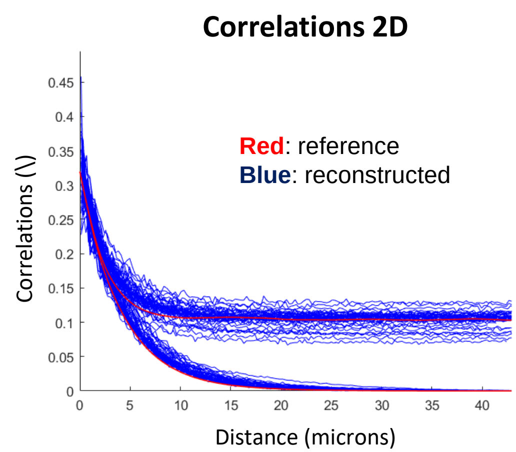
Model adopted **Lognormal-Sized + Single Sized 3D** spherical pores.

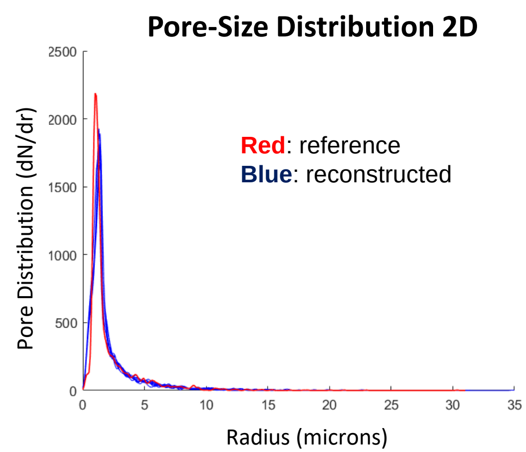
The reconstruction procedure yields:

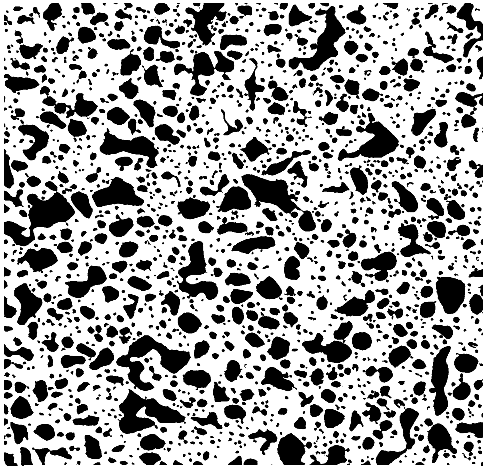
- The same **2D Pore-Size Distribution**;
- The same **2D Correlations**;
- No visible difference between reconstructed and reference image.

Image Properties

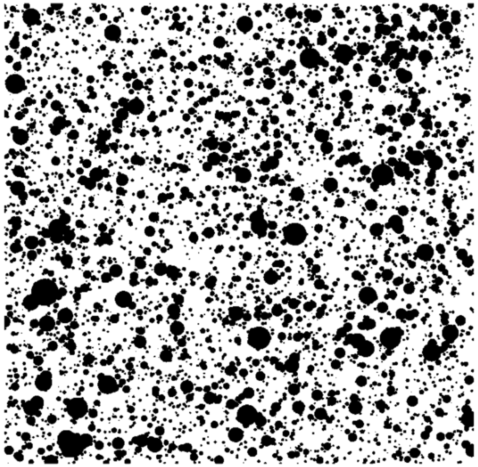
- Porosity = 0.3197
- Relative Radial Distance = 0.6524
- Pore Number Density = 0.0157
- Image Size = 408μm







Experimental 2D Section



Reconstructed 2D Section

Results

Reconstruction of the Experimental Data (2/3)

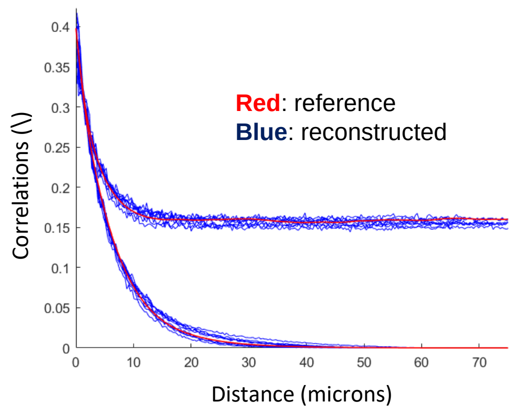
Model adopted **Lognormal-Sized + Single Sized 3D** spherical pores.

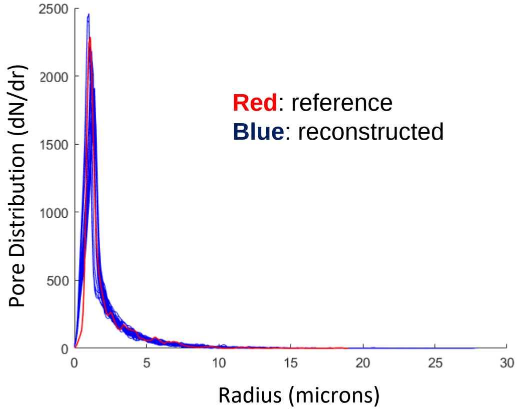
The reconstruction procedure yields:

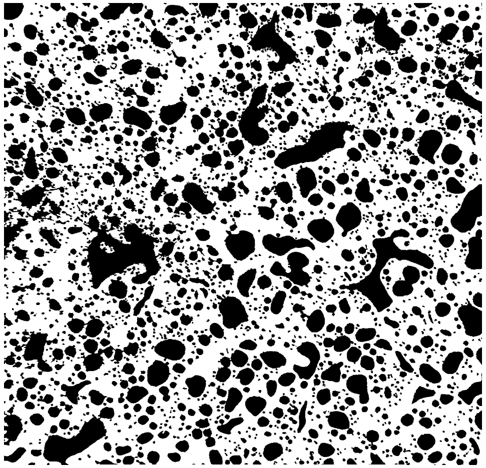
- The same **2D Pore-Size Distribution**;
- The same **2D Correlations**;
- No visible difference between reconstructed and reference image.

Image Properties

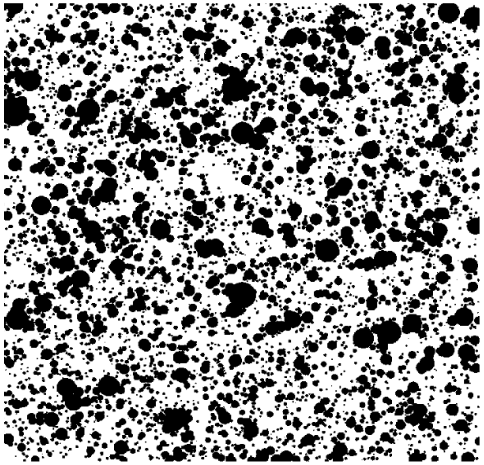
- Porosity = 0.3979
- Relative Radial Distance = 0.2854
- Pore Number Density = 0.0127
- Image Size = 425μm







Reference 2D Section



Reconstructed 2D Section

Results

Reconstruction of the Experimental Data (3/3)

Model adopted **Lognormal-Sized + Single Sized 3D** spherical pores.

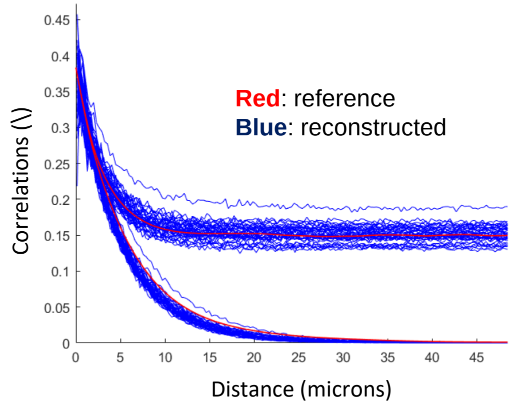
The reconstruction procedure yields:

- The same **2D Pore-Size Distribution**;
- The same **2D Correlations**;
- No visible difference between reconstructed and reference image.

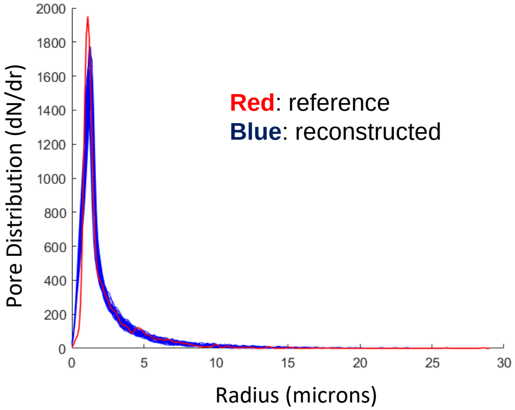
Image Properties

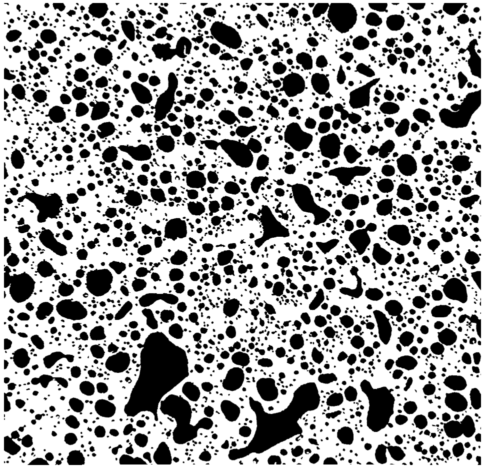
- Porosity = 0.3833
- Relative Radial Distance = 0.1262
- Pore Number Density = 0.0125
- Image Size = 425μm

Correlations 2D

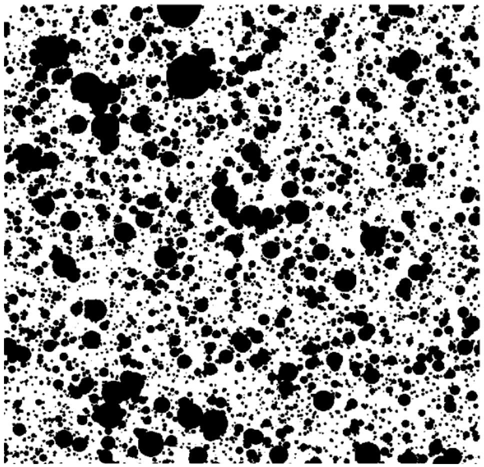


Pore-Size Distribution 2D





Reference 2D Section



Reconstructed 2D Section

Results

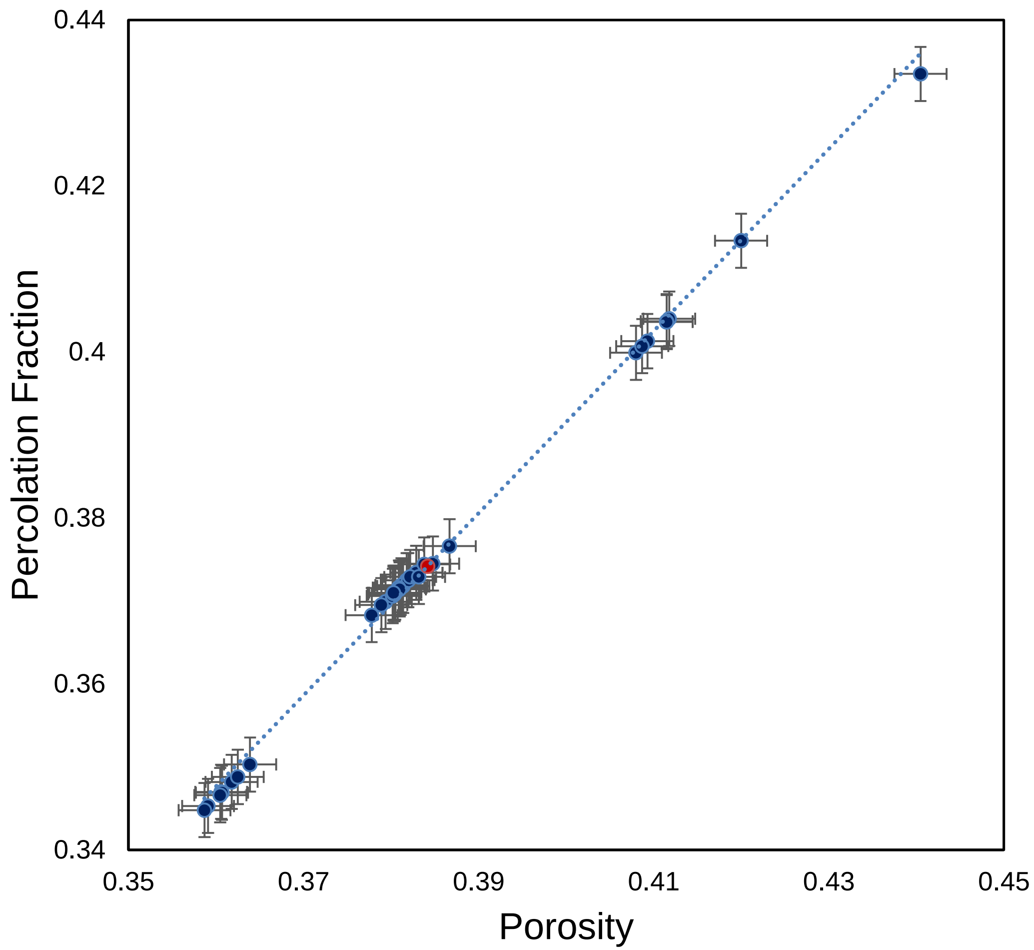
Percolation Calculation

We **perform percolation** fraction calculation of the reconstructed media and plot it against **3D porosity**. We show the results of the third image.

We have inferred both an **average value** and the **standard deviation** for the **porosity** and the **percolation threshold**.

We have thus information of the **confidence interval** of the **percolation fraction**.

This information can be used to infer the **confidence interval** of **percolation threshold**.



Conclusions

This work has developed a Genetic Algorithm for application to 3D pore reconstruction in Metallic Fuel (**first in this field of applications**).

The GA is successfully validated against synthetic media, proving a **solid reconstruction procedure**.

Reconstruction of 3D experimental samples was done with **good results on 3 different images** in three different locations of the fuel sample.

Next steps:

- Evaluation of experimental Percolation Threshold;
- Eventual development by combining a classical optimization technique with the GA (**hybrid optimization algorithm**) to improve convergence properties.

Acknowledgements

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Thank you for your kind attention!

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